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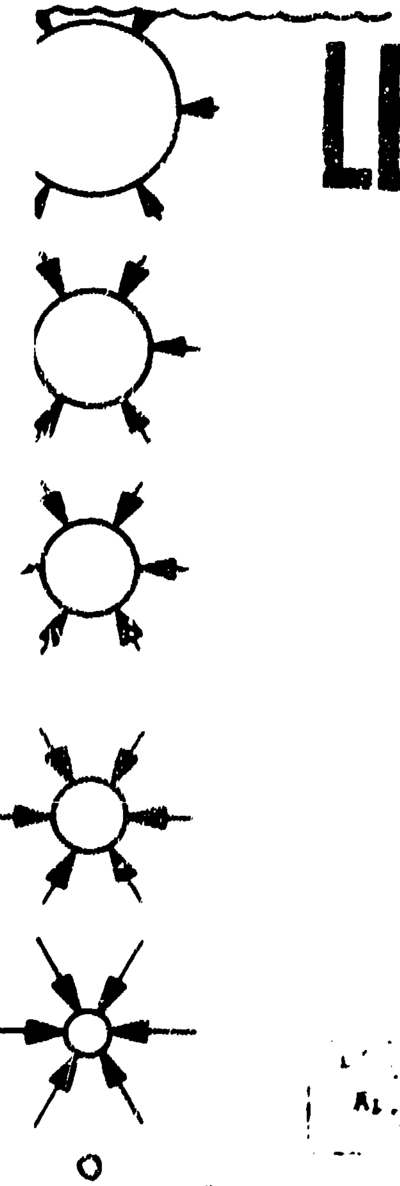

STATUS OF RESEARCH IN UNDERWATER PHYSIOLOGY

MARCH 1956

PANEL ON UNDERWATER SWIMMERS
COMMITTEE ON UNDERSEA WARFARE

National Academy of Sciences—
National Research Council

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ABSTRACT

This report has been prepared by the Physiology Group of the Panel on Underwater Swimmers as a general review of the current status of underwater physiology. In this discussion of existing information, emphasis is placed upon the interrelationship of various factors and upon a number of important questions which appear at present to be unanswered. Large new areas of underwater physiology have been opened by recent studies and should be susceptible to further investigation. The possibility now exists of a breakthrough in one or more of these areas. There is reason to expect that it will not always be necessary to base predictions of potential diving depth and duration upon the "physiological barriers" which now restrict underwater activity.

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1.0.0 THE PROBLEMS, CONCLUSIONS AND RECOMMENDATIONS

1.1.0 Introduction

The dense, cold, wet, positive-pressure environment of diving presents the individual with a pattern of physiological stresses not encountered in any other military situation. In contradistinction to the crewman of high-altitude aircraft or the submarine, the diver must be exposed to the pressure existent at his working level. This requirement introduces problems which are not readily susceptible to the engineering approach, but require solution through greatly increased knowledge of the physiological reactions to the peculiar diving environment. In a field relatively new to quantitative physiology, it appears that interrelationships of factors present but not important at sea level result in exceedingly complex phenomena in diving. The physiological stresses upon the diver vary in type and degree with changes in depth and even with the rate at which change in depth is achieved. At any depth the nature and severity of these stresses varies with his diving duration. Many unique problems to be overcome are caused by high partial pressures of the gases he must breathe, or even by the normal gaseous product of his own metabolism.

No one gas is itself devoid of toxicity; actually each of the respiratory gases appears capable of modifying the adverse effects of the others. Not only the inspired gases, but the effects of hydrostatic forces and water density alter normal respiration, which in turn affects the levels of gases in the blood delivered to the tissues. Through circulatory changes induced by the same factors, further alterations of tissue gas toxicity are brought about. Even alterations of position may conceivably modify the toxicity of a respired gas. Each type of equipment employed to provide a respirable medium underwater introduces its own peculiar emphasis upon one or more of the stresses encountered, further altering the diver's reaction to his environment.

The baseline of simple existence underwater upon which performance of useful work is based consists, therefore, of changing interrelationships of such factors as the rate of descent and ascent, depth and duration of diving, hydrostatic and inertial forces, individual and composite gas toxicities, the degree of physical exercise, type of breathing apparatus, and temperature, as well as physiological, psychological, and other factors not yet identified.

The considerable success in diving thus far has depended primarily upon empirical approximation in large numbers of subjects of the primary barriers to extension of submerged depth and duration, with restriction of diving activities to within the limits of these barriers. At present, attempts are being made to extend safely the limits of tolerance through quantitative studies of the individual physiological problems, and of the interrelationships among them. This work is now only in its early stages but it appears that there is considerable likelihood of greatly increasing the scope of underwater activity by this approach.

This report is intended primarily to present certain important problems in which lack of information is delaying extension of diving capability. The emphasis placed upon need for further research in particular areas of underwater

physiology is based in part upon information generally available and in part upon recent studies not yet contained in the published literature.

1.2.0 Conclusions and Recommendations

Naval interest in research in underwater physiology is ultimately directed toward the objectives of enabling divers and underwater swimmers to perform useful work with increased safety at greater depths for longer periods of time and to ensure an uncomplicated return to the surface. This report on the Status of Research in Underwater Physiology attempts to present, in an integrated manner, certain important physiological problems interfering with these aims. These problems have most often been considered and investigated separately. The conclusions that must be drawn from this report are that, while some of the problems lend themselves to isolated study, the interrelationships which exist among the several areas render single phases of high-pressure physiology difficult to appraise.

The complex overlapping of problems and interrelationship of physiological reactions makes the listing of specific research recommendations both difficult and undesirable. Therefore only the following rather broad restatement of the problems will be attempted:

A. Individual Gases in Respirable Media

Considerable advances could be made if the precise mechanisms responsible for the toxic effects of oxygen, carbon dioxide, and nitrogen were understood. Little information is available concerning the effects of exercise on oxygen toxicity and essentially nothing is known about permissible exposures to oxygen at shallow depths.

Of importance also is an understanding of the basis for individual variation in susceptibility to these effects and of the day-to-day variations in the single individual.

Adequate knowledge in these areas should permit a clear definition of the boundaries within which pure oxygen may be used in diving, provide opportunity for a more accurate prediction of the characteristics of new gas mixtures, and perhaps aid in the selection of personnel for specific diving and swimming assignments.

B. Use of Mixed Gases

When mixtures of gases other than air are used as a breathing mixture in diving, the effects of the individual components appear to be modified to such an extent that the ultimate utility of new combinations cannot be accurately predicted. Nitrogen at high partial pressures appears to reduce pulmonary ventilation and respiratory exchange to the extent that carbon dioxide tension is increased, which in turn may shorten the latent period for oxygen toxicity.

Alternation of high and low partial pressures of oxygen and nitrogen during a single exposure appear to relieve this situation, but detailed study is needed

to establish satisfactory time and pressure cycles for human subjects at various ambient pressures, both from the standpoint of extending permissible oxygen exposure time and the possible reduction in subsequent decompression time. Helium does not display the adverse narcotic effects of nitrogen but, in view of current helium-oxygen decompression tables, may be impractical for use in the restricted depth-time range now imposed on self-contained divers by other factors.

The potentialities of some combination of helium and nitrogen or other inert gases as an oxygen diluent deserve consideration. No studies of this nature have been undertaken to date.

C. Respiration

The physical aspects of respiration underwater remain relatively unexplored. A need for further work in this field is evidenced by the frequent subjective observations of air hunger and respiratory fatigue, particularly under conditions of heavy exercise underwater. A study of the flow characteristics of various respirable gases at elevated ambient pressures under conditions of constantly changing velocities in both the respiratory airways and breathing apparatus is indicated. Also needed is a measure of the metabolic requirements involved in the rapid displacement of comparatively large volumes of water during high ventilation rates. These data, together with information regarding underwater breathing patterns, are vitally necessary to determine whether or not radical deviations from the present design of self-contained underwater breathing apparatus are indicated.

D. Decompression

Current decompression tables for deep-sea divers are inadequate for most SCUBA applications. The time intervals of the standard air decompression tables require shortening, and the helium-oxygen decompression tables should be studied for the purpose of establishing suitable increments of time and depth in the limited depth-time ranges for SCUBA dives.

Repetitive and multilevel diving with SCUBA also presents a problem. Present requirements for decompression following repetitive diving with air may impose insurmountable limitations on certain SCUBA operations. In single multilevel dives no known tables could apply without a rigid control of the depth-time factors, and even under such controlled conditions they would undoubtedly be either questionable or unduly restrictuve. Both problems require further consideration. An analog decompression computer may be the best approach to the multilevel diving problem and study of this approach should be continued. While much time may be spent in the routine testing of decompression tables, the results would be immediately applicable and are urgently needed.

Other extant problems in decompression include the re-solution of tissue bubbles and an elucidation of the mechanisms involved in aeroembolism, mediastinal and subcutaneous emphysema and pneumothorax, with or without frank rupture of the lungs.

E. Temperature

It is generally considered that a swimmer, provided with presently available equipment, cannot be maintained in heat balance while submerged in cold water. Studies aimed at extending the useful time of exposure to cold water could profitably proceed along the two lines of improvement in compact, lightweight, flexible exposure suits and the use of physical and/or chemical devices for reducing body heat loss.

Special problems include the maintenance of manual dexterity and tactile sense, particularly of the fingers, during exposures to cold water. Circulatory and dietary studies conducted in cold, dry environments should be explored for possible extension to include immersion.

Not only the effects of exposure per se but phenomena such as the dangerous after-drop in body temperature following removal from cold water immersion require further study.

F. Toxic Contaminants in Compressed Gases

In the compression and transfer of high-pressure gases, particularly under field or emergency conditions, contaminants such as oil vapor, carbon monoxide, organic solvents and even particulate matter may be introduced. Reliable methods of detecting and removing contaminants should be determined for field use. The effects of most of these known possible contaminants have been studied at normal pressures but their possible increased adverse effects or influences on such phenomena as oxygen toxicity and nitrogen narcosis at higher pressures should be investigated.

This report describing problems not yet solved in the broad field of underwater physiology extends either directly or indirectly into almost every phase of human physiology. It appears that a comprehensive review of underwater physiology is now needed to guide a systematic approach to many of the problems being encountered in the attempt to extend diving depth and duration.

2.0.0 RESPIRATORY GASES

2.1.0 Oxygen

Except for the limitations of depth and duration imposed by oxygen toxicity, pure oxygen might be the ideal gas for use in deep diving. It is not cumulative, being consumed so rapidly in the tissues that at normal rates of decompression it is probably not possible to produce oxygen bends, even though oxygen is not eliminated from the body tissues.

Where diving duration at a particular depth exceeds the practical useful period for pure oxygen, it has been considered advisable to determine the highest permissible concentrations of oxygen which can be used as a diluent of an inert gas to minimize inert gas narcosis and bends without re-introducing the problem of oxygen toxicity. This approach requires definitive knowledge of oxygen tolerance as affected by depth, exertion and other factors. However, while oxygen tolerance is thus a factor in "mixed gas", pure oxygen, and even possibly air diving, only crude estimates of oxygen tolerance at various depths and work rates are currently available upon which to base methods of extending useful diving depth and duration.

In general it is known that at rest, oxygen tolerance at 60 feet exceeds the limits for "no-decompression" diving at this depth. No information is available regarding resting oxygen tolerance between a depth of 60 feet of sea water and sea level, where central nervous system oxygen tolerance is known to be at least 24 hours. Exercise comparable in degree to that of underwater swimming does shorten the latent period to the onset of oxygen toxicity, with the beginnings of convulsive reaction at about 40 minutes at 35 feet. One of the great deficiencies of information in the attempt to extend practical mixed-gas or oxygen diving is the void of information regarding the ultimate limits of oxygen tolerance during exercise between depths of 30 feet and 20 feet of sea water. Information presently available indicates only that toxic effects have not occurred at these depths with exposures as long as approximately 1 and 2 hours, respectively. There is as yet no indication whether oxygen toxicity can be produced at these pressures with normal levels of underwater activity, or whether the ultimate tolerance is close to the arbitrary time limits currently employed.

It is not yet known whether exercise shortens the latent period of oxygen toxicity in all subjects. The considerable variability of oxygen tolerance in and among normal individuals presents difficulties in the study of this condition, and, to some extent, limits the full use of oxygen in diving. Recent evidence suggests that changes in arterial pCO_2 (carbon dioxide tension), through an effect upon the rate of cerebral circulations, and thus upon cerebral oxygenation, may be one of the most likely causes of individual variations in oxygen tolerance. Possibly through better understanding of the factors involved in producing it, this individual variability may be reduced or a means devised for detecting the most susceptible individuals.

At rest, the effects of high oxygen partial pressures upon respiration,

blood gas transport, and cerebral circulation indicate that oxygen may exert certain of its effects through actions on normal carbon dioxide exchange. This, together with the apparent ability of altered inspired, arterial, or central levels of pCO_2 to modify the response to high inspired oxygen pressures, indicates that studies of the physiological or toxic reactions to oxygen must be closely correlated with studies of the concurrent alterations of carbon dioxide exchange. The effects of high oxygen pressures upon the respiratory and circulatory responses to various levels of exercise have only just begun to be investigated. The physiological responses to oxygen during exercise appear at this stage to be considerably different from those at rest. Here again, studies to date indicate that interrelationships of the levels of exercise, carbon dioxide exchange, inspired pO_2, respiratory responses, and circulatory alteration are mutually interdependent. The composite effect upon oxygen tolerance varies considerably with changes in any one of these factors. The details of these relationships require much further study.

2.1.1 Effects of Inert Gases on Oxygen Toxicity

It has recently become questionable whether, as had been heretofore considered, the tension of an "inert" gas such as nitrogen is without influence upon the tolerance to a particular high tension of oxygen. Preliminary studies suggest that convulsive seizures occur earlier in the presence of nitrogen than they do in its absence, even though inspired pO_2 is the same. Exercise hyperventilation is relatively low at high ambient pressures when mixtures of oxygen and nitrogen are inhaled; it is yet not certain whether the associated extremely high alveolar pCO_2, oxygen, or both are responsible for the seizures. Nor is it known whether nitrogen, through a narcotic action, directly alters the cortical response to high pO_2, or whether any action of high nitrogen tensions per se is related to alternation of pulmonary ventilation and alveolar pCO_2. The degree to which such effects may be altered by increasing diving depth and duration or even whether other as yet unknown actions of "inert" gases can modify oxygen tolerance is still unanswered.

The various hydrostatic and inertial forces and changes in gas density encountered underwater may conceivably affect pulmonary ventilation and circulation and, through such effects, alter carbon dioxide exchange and oxygen tolerance. Essentially, no information is available regarding these questions.

2.1.2 Intermittent High and Low Oxygen Tension

Most studies of oxygen toxicity have involved continuous exposures to pure oxygen at high pressure. If oxygen toxicity develops slowly, as indicated by the very long latent period at moderate pressures, and is rapidly reversed on lowering oxygen tension, as also appears to be the case, an alternation of high and low oxygen tensions in the respired gas mixture might conceivably extend greatly the working time at increased ambient pressure. Field experiments in man during World War II suggested that this occurred. Recent, better-controlled st[illegible]s in guinea pigs at 3.0 atmospheres indicate that the latent period for the [illegible]igns of oxygen intolerance is extended from about 4 hours breathing oxygen c[illegible]ously, to about 19 hours on a schedule of oxygen inhalation for 30 minutes, alternating with normal inspired pO_2 for ten minutes. Since such a schedule not

only greatly extends oxygen tolerance but appears to permit nitrogen elimination during the periods of oxygen breathing, simultaneous solution of the problems of bends and oxygen intolerance may be possible. No controlled studies of this nature have as yet been carried out in man.

2.1.3 Biochemical and Bioelectric Phenomena

A considerable advance was made during World War II in delineating effects of high oxygen pressures upon enzyme systems, particularly of brain tissue. Additional studies of this nature, making effective use of recent advances in enzyme chemistry, could add to the excellent past work and extend comprehension of the biochemical basis for oxygen intolerance. It appears particularly desirable, now that physiological effects of high oxygen upon men are being studied quantitatively, to attempt establishment of a link of technique or experimental condition between in vitro and in vivo studies to facilitate ultimate correlation of data obtained through these different approaches.

Thus far no systematic neurophysiological studies of oxygen toxicity have been made, though numerous workers have demonstrated measureable bioelectric phenomena in parts of the neuraxis during exposure to high oxygen pressures. It is possible that measurement of bioelectric phenomena may provide an early and sensitive index of oxygen intolerance in studies of oxygen toxicity, or of its modification by agents such as drugs or other gases.

2.1.4 Pulmonary Effects of Oxygen

There is no evidence for the occurrence of pulmonary irritation in humans subjected to inhalation of oxygen at high ambient pressures. Total length of exposure of human subjects has, however, rarely exceeded two hours at 2 to 4 atmospheres. Nevertheless, one of the principal results of the more prolonged exposure of certain laboratory animals to oxygen is pulmonary pathology. Certainly with common experimental animals (rats, guinea pigs, rabbits, cats, and dogs) pulmonary damage, rather than central nervous system toxicity, is quite frequently the factor limiting exposure. The damage becomes severe with increased duration of exposure to high oxygen pressures. At autopsy the lungs of these animals present the picture of severe congestion with edema and atelectasis. The gross appearance resembles that of liver or spleen. There is much evidence supporting an endocrine influence on the degree of pulmonary irritation by oxygen, both hypophysectomy and adrenalectomy providing a significant degree of protection. The pulmonary changes can in a large measure be reversed by positive pressure insufflation of the lungs. The indication thus is that a principal component of the oxygen effect may be diffuse atelectasis. Since pulmonary changes can decrease the oxygenation of arterial blood, the central nervous form of oxygen toxicity may be prevented in animals susceptible to pulmonary effects of high oxygen pressures. Much work remains to be done in elucidating the mechanism of the pulmonary damage, and ways of alleviating it must be found in order to permit more definitive studies in animals of the central nervous system effects of high oxygen pressures.

2.2.0 Carbon Dioxide

Carbon dioxide, produced by the body at a high rate during exercise, has powerful physiological and toxic effects of its own. It can also indirectly affect the diver through modification of oxygen tolerance. Until recently, carbon dioxide was considered as a factor in diving only if important amounts were inhaled, e.g., because of high apparatus dead space, inadequate helmet wash-out or inadequate carbon dioxide absorption in rebreathing systems. These causes of direct carbon dioxide excess are primarily related to the design of breathing apparatus and are still common where equipment design or maintenance is deficient. In general, the inhalation of carbon dioxide appears to exert such effects as respiratory stimulation, cerebral vasodilation, headache, and, if inspired tension exceeds the equivalent of 10% CO_2 at sea level, can lead to confusion and unconsciousness. Still higher inspired levels (20% to 30%) produce myoclonic twitchings or convulsions not dissimilar in appearance to those of oxygen toxicity. The latent period for such carbon dioxide convulsions (one to two minutes) is extremely short as compared with that for oxygen convulsions.

2.2.1 Carbon Dioxide and Oxygen Toxicity

When carbon dioxide is inhaled with oxygen, oxygen tolerance is decreased, apparently due in part to the increase in oxygen delivery to the brain resulting from cerebral vasodilation by high carbon dioxide tensions. The primary and secondary effects of inhaled carbon dioxide have been subjected to relatively little study under positive pressure. While the relationships of respiratory responses to increased inhaled carbon dioxide under resting conditions at sea level are becoming more clear, circulatory responses even under these conditions are less well understood. The maximum increase in cerebral circulation which can be produced by carbon dioxide is not yet known, nor is it completely clear whether inspired carbon dioxide dilates the cerebral vessels through a direct action upon cerebral arterioles or through other mechanisms. Information regarding the effects of increasing inspired carbon dioxide concentrations upon judgment, reflexes and motor performance is inadequate for determining safe levels of carbon dioxide inhalation in diving. The underlying biochemical and neurophysiological mechanisms of carbon dioxide convulsions also require study, particularly in regard to interrelationships with the convulsions of oxygen toxicity.

Just as high levels of inspired carbon dioxide or the pulmonary retention of carbon dioxide can diminish oxygen tolerance, it appears from the results of animal studies that hyperventilation, with a resultant lowering of arterial carbon dioxide tension, can increase oxygen tolerance. These observations may have considerable relationship to the powerful cerebral vasoconstrictor action of hypocapnea. As one of the few presently evident possibilities for lowering brain tissue pO_2 at a given inspired oxygen tension, the effects of hypocapnea combined with hyperoxia upon cerebral hemodynamics, cerebral gas exchange, and the tolerance to high oxygen tensions deserve study.

Cerebral blood flow begins to be increased when carbon dioxide concentrations above 2% are inspired at sea level. However, the minimal inspired tension of carbon dioxide which will decrease oxygen tolerance is not yet known, nor is the lowest oxygen tension which will produce toxic symptoms in the pres-

ance of maximal cerebral vasodilation by carbon dioxide. While either exercise or carbon dioxide can decrease tolerance to oxygen, no studies of the combined effects of exercise and high inspired carbon dioxide tensions upon oxygen tolerance have been made. For all of these studies a base line of tolerance and its variance when pure oxygen is breathed must be established.

2.2.2 Carbon Dioxide Autointoxication

During the past few years it has become apparent that carbon dioxide may produce toxic effects in diving, not only by reinhalation from defective apparatus, but through its inadequate elimination from the body. Carbon dioxide autointoxication presumably occurs whenever pulmonary ventilation is low with respect to the rate of metabolic carbon dioxide production. Conceivably factors such as resistance to breathing, training, partial depression of the respiratory centers, and breathholding may lead to inadequate removal of carbon dioxide from the lungs, blood and tissues, resulting in a critical degree of hypercapnea. This problem, now only in the early stages of investigation at positive pressure, has an important relationship, not only to primary carbon dioxide intoxication as a possible cause of "shallow water blackout" or even convulsions, but also to the pharmacology of oxygen toxicity and nitrogen narcosis, the physiology of respiratory resistance and exercise, and probably numerous other aspects of diving. Considerable information bearing upon this subject should arise in the course of general sea-level studies of the physiology of pulmonary ventilation, carbon dioxide and oxygen, exercise, respiratory control and even the respiratory effects of narcotic and stimulant drugs. The ultimate delineation of the scope of this problem will require further study at increased ambient pressures.

2.3.0 Nitrogen

Whenever a diver is at depth breathing air or any other nitrogen-oxygen mixture, he is exposed to unusual partial pressures of nitrogen. Such exposure can involve two major untoward effects: namely, 1) solution of this "inert" gas in the blood and tissues while under pressure may give rise to decompression problems on subsequent ascent; and, 2) increased nitrogen pressures may cause depression of the central nervous system even though gaseous nitrogen is generally considered inert. The overt manifestation of the latter effect is called nitrogen narcosis or compressed air-intoxication. In recent years, it has achieved popular recognition as "Rapture of the Depths". The subjective experience is not unlike alcohol intoxication or mild nitrous oxide anesthesia. The mechanism of this effect is no better understood than that of other narcotic gases.

2.3.1 Individual Differences in Susceptibility to Nitrogen Narcosis

Individuals differ in their susceptibility to nitrogen narcosis, but most divers are aware of some mental impairment at a depth of 100 feet when breathing air. Performance of tasks which require much thought, judgment, or manual skill makes the impairment more evident. On approaching 300 feet, the average diver is virtually useless, and this depth is accepted as the practical limit for useful air dives. Even with deep-sea diving equipment and good telephone communication with the surface, impairment of the diver's sensorium is a definite hindrance in working dives beyond 150 feet. In diving with self-contained under-

water breathing apparatus (SCUBA), the same degree of impairment can affect performance even more adversely and can jeopardize the diver's safety as well.

2.3.2 Central Nervous System Effects

Even though the existence of a central narcotic effect of nitrogen has been recognized for many years, much more information is required. The actual types, degrees, and consequences of functional impairment produced by nitrogen at various partial pressures remain ill-defined. The extent of individual variation in susceptibility needs to be ascertained, and reliable means of identifying unusually susceptible individuals are needed. If there are any indulgence or abstinence influences which cause proneness to nitrogen narcosis to increase or decrease, these have not been identified. Practical methods of improving performance under increased nitrogen pressures would be of considerable value; this approach has received essentially no attention.

Recent investigations indicate that the depressant action of nitrogen may include the more elemental functions of the brain as well as the mental processes. Depression of respiration with retention of carbon dioxide has been observed in working divers exposed to increased nitrogen pressures. The consequences of this apparent medullary depression may include not only direct carbon dioxide autointoxication but also increased susceptibility to oxygen poisoning in the use of nitrogen-oxygen mixtures. These effects appear possible even when the influence of nitrogen upon the higher centers is not subjectively pronounced. The exact mechanism of the observed phenomena is still uncertain, and the possibility of actions on the circulation and other functions has not been ruled out. The interrelationships with oxygen toxicity may prove to be complex. The extent of individual differences in susceptibility to this form of nitrogen depression has barely been explored, but it appears that experienced divers may be unusually susceptible.

The observations suggesting medullary depression require verification and further study. The possibility of effects on functions other than respiration must be investigated. The exact significance of any nitrogen depression of the lower centers must be defined quantitatively relative to both oxygen toxicity and carbon dioxide intoxication. Understanding of both aspects will require further study of its mechanisms as well as a delineation of its effects and consequences. Individual differences and means of personnel selection also require study, especially in view of apparent peculiarities of divers in regard to respiratory control. Since these depressant phenomena jeopardize the utility of nitrogen-oxygen mixtures in essential diving operations, means of circumvention must be sought. Certainly the effects of nitrogen will remain a physiological problem of distinct practical importance as long as air or other nitrogen-oxygen mixtures are used in diving.

2.4.0 Helium

Helium lacks the depressant effects of nitrogen. At least, these effects are slight even at considerable diving depths. The respiratory depression observed with nitrogen at depth is not seen when helium is substituted, and the preservation of mental clarity with helium is well known.

At present, helium is the only "non-depressant", inert gas which is known to be a fully practical substitute for nitrogen in breathing mixtures. The technique of helium-oxygen diving, as currently employed, is highly successful in making useful dives possible at greater depths than are possible with air. The current record depths are 561 feet (pressure tank) and 500 feet (open sea). There is no known physiological reason why these records cannot be exceeded.

2.4.1 Decompression

Contrary to original expectations and to information still to be found in textbooks, the use of helium does not eliminate or greatly lessen the problem of decompression in most diving situations. It provides such an advantage in long, deep dives, but in the depth-time range of practical SCUBA diving the use of helium actually appears to increase the amount of decompression time required. According to present knowledge, a dive which requires less than one hour of total decompression time will generally yield a better ratio of working time to decompression time if nitrogen is used rather than helium.

2.4.2 Breathing Resistance

In addition to its lack of depressant effects, helium also reduces the respiratory resistance encountered in SCUBA circuits and in the diver's own airways at depth. Since excessive work-of-breathing may limit the degree of physical exertion possible in deep dives, this may be a real advantage of helium-oxygen breathing. It is not yet known whether the elimination of carbon dioxide from the lungs is significantly interfered with by increased gas density at depth. Should this be the case, the use of helium would be desirable from this standpoint also. If medullary depression by nitrogen is involved in the enhanced susceptibility to oxygen poisoning observed in the use of nitrogen-oxygen mixtures, the operational objectives of "mixed gas" diving may have to be sought with helium. Then the main problems related to helium will be those concerned with decompression. To what extent increased decompression time, apparently required by the use of helium in the SCUBA depth-duration range, would limit advance, remains to be seen.

2.5.0 Toxic Inhalants

2.5.1 Carbon Monoxide

The SCUBA diver is susceptible to harm from any noxious substance which finds its way into his gas cylinders or breathing circuit. Among the possibilities, carbon monoxide is probably the most serious. Its presence can come about either through intake of exhaust gas by the compressor or through formation of carbon monoxide by the breakdown of lubricating oil in the compressor itself. The former is particularly possible with portable gasoline-driven air compressors used in the field. The latter is a potential danger wherever an oil-lubricated compressor must be used.

The toxicity of carbon monoxide at sea level is proportional to the amount of carboxyhemoglobin formed. While at depth, a diver may tolerate considerably higher ratios of carboxyhemoglobin because, due to the increased partial pressure of oxygen at depth, some of his oxygen transport requirements are met by

oxygen in simple solution. However, since the reconversion of carboxyhemoglobin to oxyhemoglobin is relatively slow, he may be in immediate difficulty on ascent.

If the carboxyhemoglobin formation resulting from a given inspired concentration of carbon monoxide is proportional to the ambient pressure, the permissible concentration in diving may be exceedingly small. However, it is not certain that this relationship applies since the equilibrium ratio of carboxyhemoglobin to oxyhemoglobin at high pressures has not been established. It is conceivable that high ambient pressures may influence the initial rate of carboxyhemoglobin formation but not the equilibrium amount, since the oxygen tension of respired air is also increased under these circumstances. Without definite information on this subject is is impossible to specify the safe limits of carbon monoxide content for gases used in SCUBA or even to assess the actual importance of this potential hazard. It is also impossible to be certain whether available methods of carbon monoxide analysis which can be used in the field are sufficiently sensitive, whether practical methods of removing the gas are adequate, or whether the use of certain types of compressors should be interdicted entirely.

2.5.2 Oil Vapor

Oil vapor is a common contaminant of SCUBA air supplies. Any oil-lubricated compressor will yield air containing at least a trace and badly designed or poorly maintained compressors may produce a large amount of oil vapor. It is known that lipoid pneumonia and related disorders can result from inhalation of oil vapor. The possibility of carcinogenesis from oil constituents, while probably remote, cannot be ignored completely. Although many divers have undoubtedly had considerable exposure to inspired oil vapor, there has been little clinical evidence of harm. However, a search for such evidence, especially of delayed and chronic effects, might be illuminating. At the present time, it is not even possible to say whether oil vapor is a serious diving hazard.

2.5.3 Miscellaneous Inhalants

The effects of any noxious gas, fume, or vapor which contaminates a diver's gas supply might be intensified by increased ambient pressure. For example, even jokes about "compressed smog" may have an element of unpleasant truth. Ozone has not been exonerated as a pulmonary irritant. A variety of otherwise ill-explained diving accidents or sequelae may have their explanation in contaminants. For example, divers using certain open circuit units consistently reported symptoms closely resembling "metal-fume fever" following otherwise unexceptional dives. It is possible that certain methods of treating the interior of cylinders could give rise to such an effect.

Although the incidence of accidents from causes such as those mentioned above is fortunately small, many questions arise. It would be highly desirable to know the interrelationship between the toxicity of carbon monoxide and increased ambient pressure. Definite information about the tolerable amount of oil vapor and the possible effects of other contaminants would be worthwhile. Meanwhile it remains necessary to seek means of preventing contamination of air supplies and reliably removing noxious agents.

3.0.0 DECOMPRESSION

3.1.0 General

When a diver is at depth, the inert gas of his breathing medium goes into solution in his blood and tissues. On subsequent ascent, an excess of this dissolved gas can cause formation of bubbles and result in decompression sickness. Prevention of decompression sickness requires either limitation of the amount of dissolved gas by restriction of the diver's depth and time of exposure, provision of decompression stops to permit elimination of the gas on ascent, or both.

Decompression sickness itself is a serious potential problem. Its manifestations range from local pain to severe central nervous system involvement, and its sequelae can include permanent injury or death. Recompression is the only effective treatment, and adequate therapy can require as long as 38 hours in a recompression chamber. Where treatment facilities are distant or lacking, decompression sickness must be avoided at all costs. Assuring proper decompression imposes formidable limitations on all kinds of diving, and these limitations are particularly serious in military applications of SCUBA. The limits of the diver's air supply or the circumstances of the dive may make normal stage decompression extremely difficult or impossible; avoiding the necessity for stage decompression may make the practical working time for deep diving impossibly short. The situation is difficult enough even when adequate, applicable decompression tables are available for the time of diving involved. Where they are not available, the problems are almost insuperable. In some of the urgent military applications of SCUBA, existing techniques for managing decompression are entirely inadequate.

Several different types of dive can be encountered and these have different implications as to decompression procedures. Several modes of decompression are available and there are a number of approaches to reduction of the decompression time required.

3.2.0 Standard Air Diving

A "standard" dive can be defined as one in which the diver descends to a known depth, remains there for a known period of time and ascends. Most conventional air-hose diving and some SCUBA diving falls in this category and all of the Navy's current decompression tables are designed primarily for it.

3.2.1 Regular Decompression

Regular decompression implies that all of the decompression stops are made in the water and that the same breathing medium is used throughout. The Navy Standard Decompression Table (Air) applies to these conditions. This is an adequate table for the purposes for which it was designed, namely standard air dives with conventional suit and helmet and with a recompression chamber nearby. It approaches adequacy for standard diving with SCUBA, but certain shortcomings become evident even in this connection. For example, the table provides only rather large and irregular increments of diving time. This means that

a diver who overstays a given increment by even one minute must, to be safe, take the decompression specified for the next increment. This may be much longer than necessary, but on-the-spot interpolation is neither practical nor safe. The added time is seldom of much concern to the air-hose diver. He has ample air supply, surface personnel are in control, and the communication is good. The SCUBA diver is not so fortunate, and the extra time may place him at a very serious disadvantage. Smaller increments of bottom time would be very valuable in SCUBA diving.

On the other hand, a SCUBA diver who follows the standard decompression table precisely may not invariably receive adequate decompression. The table was not intended to be 100% safe in preventing bends, since allowing for all individuals and all conditions would impose a large burden of unnecessary decompression on the majority. An occasional case of decompression sickness is acceptable if facilities for prompt and adequate recompression are available. In SCUBA diving, this situation is more likely to be the exception than the rule, and precise control of the diver's depth and time is also less likely than in conventional diving. For these reasons, certain portions of the table should probably be made somewhat more conservative for SCUBA use. At the same time, however, it might be possible to liberalize other parts of the table without compromising safety, and any safe reduction of decompression time would be of obvious advantage to the SCUBA diver.

Within certain limits of depth and exposure time, no decompression stops are required. The standard table specifies a "no stop" time for each 10-foot increment of depth from 40 to 130 feet. These limits are of particular interest to the SCUBA diver since avoiding the necessity for stops greatly simplifies the diving procedure. Whether the "no stop" times indicated in the present table are optimal is of obvious importance.

3.2.2 Surface Decompression

Surface decompression allows the diver to spend a considerable portion of his decompression time in a recompression chamber rather than in the water. This is possible, within certain limits, if the diver can be put in a chamber immediately upon surfacing. Although it has seldom been exploited in SCUBA diving and would not often be possible, this procedure would have great advantages in some SCUBA operations.

3.2.3 Oxygen Decompression

Oxygen decompression involving a shift to pure oxygen on ascent at a depth where this can be done safely (current procedure is to begin oxygen breathing at 50 feet), shortens decompression by hastening the elimination of inert gas. A highly successful combination of surface decompression and oxygen decompression is provided by the Navy's "Surface Decompression Table Using Oxygen". This has proved both safe and extremely advantageous in routine use, and it should be applicable to SCUBA diving without modification wherever a chamber with oxygen-breathing facilities is immediately accessible. The same table could probably be applied to the use of oxygen in underwater decompression with SCUBA, but it should be tested specifically for such use. The saving of time

would amply justify the trouble of shifting the breathing medium in many circumstances.

3.3.0 Repetitive and Multilevel Air Diving ("Irregular Dives")

The decompression procedures discussed above are designed not only for "standard" diving but also primarily for dives separated by considerable intervals of time. The only current provision for repetitive diving (successive dives made at relatively short intervals) consists of a single rule-of-thumb. This states that if more than one dive is made within a 12-hour period, the decompression for each succeeding dive shall be that specified for the combined bottom-times of all exposures during that period and for the actual depth of the latest dive.

In many types of SCUBA operation, it may be necessary or highly desirable for a diver to make several dives at very short intervals. In such cases, the existing rule appears to be prohibitively over-safe for many combinations of depth and time, but it may well be unsafe in others. A better means of setting limits and determining proper decompression in repetitive diving is badly needed. An approach to this is provided by tables set forth by French investigators, but these appear to be neither as complete as might be desired nor as well-tested as necessary for outright adoption.

A similar but even more difficult problem is presented by "multilevel" dives, those which involve spending a variety of times at a number of different depths during the course of a single exposure. The SCUBA diver's freedom of movement in all directions and the nature of his assignments make such dives frequent a often essential. Even if the exact length of time at each depth could be tabula ., present information would not permit truly appropriate decompression to be specified. Decompressing for the deepest depth and the total time, which is about the only safe rule which can be followed at present, would be so over-safe and restrictive in many situations that the desired operations would be rendered impossible.

There is probably no fully satisfactory solution to the problem of decompression in multilevel diving, but it is probable that more realistic rules could be formulated for certain patterns of dive. If so, many operations could be planned to fit these patterns. The idea of a "decompression computer" to be worn by the diver appears most promising. Suggestions along these lines involve a system which would respond to ambient-pressure changes and exposure times in a manner analogous to that of the solution and elimination of nitrogen in the tissues. By providing a warning when serious supersaturation became imminent, such an aid would permit the diver to govern his ascent. Considering the variability in susceptibility to bends, no mechanical device could be expected to provide more than a safe approximation of optimum decompression. However, even this could be a decided improvement for both multilevel and repetitive diving.

3.4.0 Mixed Gas Diving

3.4.1 Nitrogen-Oxygen Diving

In certain military applications, the decompression required in air diving would be impractical even with the best possible techniques and tables. Consequently, some method of reducing decompression requirements to their absolute minimum is needed. The most obvious method of accomplishing this reduction is to limit the partial pressure of inert gas to which the diver is exposed. This can be done by increasing the proportion of oxygen in the breathing mixture. However, the oxygen level must be kept within safe limits relative to oxygen poisoning.

Calculations based on known tolerance to oxygen exposure at various depths have indicated that the use of "high-oxygen mixtures" could safely permit marked extension of "no stop" decompression limits and great reduction of decompression time. However, in preliminary studies with nitrogen-oxygen mixtures, toxic symptoms appeared in much shorter time than when the same partial pressure of oxygen is encountered with pure oxygen as the breathing medium. Subsequent studies indicated that carbon dioxide retention, due to insufficient pulmonary ventilation, was a common occurrence in divers breathing nitrogen-oxygen mixtures during work at depth. Such hypoventilation may explain the apparently increased susceptibility to oxygen toxicity and the occurrence of carbon dioxide intoxication. These findings suggest serious limitations in the potentialities of nitrogen-oxygen diving and have important implications in other types of diving as well. This phenomenon requires much further study.

3.4.2 Helium-Oxygen Diving

The technique of helium-oxygen diving is already well developed and has been used successfully for over 15 years. The procedure involves using oxygen percentages scaled according to the depth; oxygen decompression is an integral part of the technique, and surface decompression is employed routinely. The present helium-oxygen technique could be adapted to SCUBA diving with very little change, but several physiological problems must be solved before the adaption would be fully satisfactory. The oxygen-exposure limits specified in current helium-oxygen techniques are almost certainly not safe enough for working dives of significant duration. However, helium does not appear to share the respiratory depressant effects observed with nitrogen-oxygen mixtures. If it does not, the partial pressure limits for oxygen in helium-oxygen mixtures could probably be similar to those for exposure to pure oxygen. In any event, specific investigation is required.

Present helium-oxygen decompression technique requires shifting the breathing medium to pure oxygen at 50 feet on ascent, and there are no decompression stops shallower than 40 feet. For SCUBA use it might be more desirable to shift to oxygen at 40 feet and to spend the remainder of decompression time at a succession of shallower stops. However, shifting at 40 feet would increase the decompression time required, and the tables would have to be completely recalculated and retested in either case. In some situations, shifting to oxygen might prove impractical. If so, new tables permitting decompression on

the original breathing mixture would be required.

It appears inevitable that a SCUBA dive made on a helium-oxygen mixture will require longer decompression than an identical dive made with the corresponding nitrogen-oxygen breathing medium unless the dive is deeper and longer than is at present anticipated in SCUBA operations. It is possible that the decompression specified by the present helium-oxygen tables is more than adequate in the short, shallow range of diving. This possibility will certainly need investigation if it appears likely that the use of helium-oxygen must take over the role intended for nitrogen-oxygen mixtures.

3.4.3 Multiple Inert-Gas Mixtures

A recurrent proposal concerns the use of a combination of two or more inert gases as a diluent for oxygen. While this does not appear likely to produce any marked saving of decompression time, it might permit balancing the distinctive properties of nitrogen and helium in a beneficial manner. This possibility deserves further theoretical and experimental study.

3.4.4 Possible Refinements of the "Mixed Gas" Principle

The above discussion of oxygen-nitrogen or oxygen-helium mixtures assumes the use of a breathing medium of reasonably constant percentage composition throughout the dive or at least until the beginning of decompression. While this appears to be the simplest approach to the reduction of decompression time, it is probably not the most effective. Several alternative methods which have been proposed offer potentially fruitful subjects for consideration and research:

a. Constant Partial Pressure of Inspired Oxygen. Maintenance of a given partial pressure of oxygen regardless of the diver's depth would keep the exposure to an inert gas close to the level required to avoid oxygen poisoning at a particular depth. The ultimate approach of this sort might involve automatic reduction of the oxygen tension as time progressed, permitting a higher mean oxygen tension for the dive and thus a minimum uptake of inert gas.

b. Exertion-governed Oxygen Percentage. A man is most susceptible to oxygen poisoning when he is working. During rest or minimal exertion, his tolerance is considerably greater. Consequently, a relatively high mean oxygen partial pressure could be tolerated if a drop in the oxygen level could be assured during periods of exertion.

c. Interrupted Oxygen Exposure. Interrupted oxygen exposure (2.1.2) offers the possibility of extending tolerance to high oxygen pressures if interruptions are provided at appropriate intervals. In this way, the mean oxygen tension for a dive could be very high indeed and the inert-gas exposure correspondingly limited.

All of these possibilities of extending the potentialities of nitrogen-oxygen diving pose serious physiological problems concerned with both oxygen tolerance

and the intricacies of inert gas exchange and decompression. Unfortunately, taking positive advantage of the characteristics of such systems would require much more information than is now available concerning oxygen tolerance and inert gas exchange in the presence of fluctuating tensions. The ultimate value of such systems cannot yet be assessed with confidence. It is possible, however, that a moderate amount of experimentation could at least allow a significant gain over present approaches, obviating the need for certain more laborious decompression studies.

3.5.0 Derivation of Decompression Tables

Development of a decompression table which is safe but not excessively conservative is a difficult enterprise at best. It is rendered more difficult by each additional variable and by each departure from "standard" practice, and both of these factors loom large in SCUBA decompression problems.

The most crucial factor in the derivation of tables is the quality of predictions which can be made on the basis of theoretical calculations and previous experience. It is obviously impossible to base a table entirely upon an accumulation of accidental instances of bends. The investigator must have some method of deriving working hypotheses which can then be tested. If the basis of these is faulty, a large burden is thrown upon actual experimentation. This, in turn, is extremely laborious and time consuming because of the extent of inter- and intra-individual variability and the ill-defined influences of a variety of factors. Many experimental dives must be made before the appropriateness of a given part of the table can be considered certain. If the basic theory is faulty, it will also be difficult to interpret and apply the results of experimentation.

Available methods of computing decompression tables obviously leave much to be desired. The theoretical basis appears to be quite inadequate. Assessment of some of the proposed methods of handling the decompression problem mentioned above offers a good example of the existing difficulty. Considering them with the aid of present methods and theories might provide insight into their implications and probable value. However, the conclusions would have to be very tentative, subject to actual experiments and, in some cases, these experiments would have to be very extensive. In the case of many uncertain but potentially fruitful possibilities, such consideration and investigation is a practical impossibility at present.

In spite of the need for basic information, further work in this area cannot wait for basic research to be accomplished. The immediate needs are too great. Such research should certainly progress simultaneously with the primitive, laborious efforts which its lack makes necessary. Research in the area of decompression sickness has thus far been directed primarily toward the mechanisms of bubble formation. Studies related to the treatment of decompression sickness, e.g., the reabsorption of gas bubbles, are also required.

3.6.0 Air Embolism and Related Problems

As used in diving, the term "air embolism" refers to a type of accident which may occur on ascent but which is an entity distinct from decompression

sickness. The central nervous system is almost invariably involved. Most frequently, the accident has been associated with relatively rapid ascent without breathing apparatus, as in the "free ascent" method of submarine escape and in emergency ascent following failure of SCUBA. It does not occur on ascent from "breathholding" dives unless the diver has had access to additional air at depth. The accident is extremely rare, but it has followed routine ascents with conventional submarine escape and deep-sea diving equipment and even ascents in a dry-pressure chamber.

Usually air embolism is clearly associated with breathholding or inadequate exhalation during ascent. It is attributed to distention of the lungs by the pressure of expanding pulmonary gas. This presumably tears lung tissue and forces gas into the circulation. Embolization of the cerebral circulation by bubbles is considered the immediate cause of symptoms. Victims occasionally show minimal central nervous system defects, but profound neurological involvement including unconsciousness and convulsions is much more common in recognizable cases. At least some favorable response generally occurs on prompt recompression and many have been dramatically and completely relieved by exposure to increased ambient pressure, presumably because this compresses the offending bubbles to non-symptomatic size. If such treatment is delayed or omitted, death is the usual outcome in cases which display severe symptoms.

Frank rupture of the lungs, mediastinal and/or subcutaneous emphysema, and possibly pneumothorax without gross pulmonary rupture, may be associated with air embolism. Any of these may occur alone under similar circumstances.

Current assumptions concerning the mechanism of air embolism appear justifiable and have in part been verified experimentally. However, they are not completely satisfying. Many details are obscure. As a result, it is difficult to reach firm conclusions about the best method of making emergency ascents or about the exact procedure for optimum treatment.

4.0.0 RESPIRATION

In the foregoing sections of this report, physical and physiological effects of individual gases and gas mixtures have been considered primarily with respect to their behavior when contained within the blood stream and tissues. If all of the respiratory problems related to gas toxicities could be eliminated, the success of a diver's attempts to perform effectively would still depend upon a satisfactory delivery of a respirable medium to the lungs themselves. To be completely satisfactory, this delivery must be such that tolerable limits of breathing resistance are not exceeded and adequate pulmonary ventilation is assured at all times. Most of the problems in the field of the mechanics of breathing underwater are related to one or the other of these conditions.

4.1.0 Breathing Resistance

With the establishment of acceptable limits for both positive and negative breathing resistance, providing a breathing device to function within these limits would be reduced to a matter of engineering. While the problems of breathing resistance at normal pressure in air are similar to those existing under water, there is no assurance that the same values for sea-level conditions would apply to the rather dissimilar underwater environment. Noncontroversial limits have not been determined for either positive or negative breathing resistance for extended periods of time even at one atmosphere.

Responses to positive pressure breathing include changes in alveolar pO_2 and pCO_2, peripheral vasoconstriction and general blood pressure changes, and alteration of the ventilation/perfusion ratio. Most of the work relating these responses has been conducted with the subjects in air, at sea-level pressure or at altitude. In an underwater environment, some of these responses undoubtedly would be modified by hydrostatic influences upon the circulation, a normal slowing of the heart rate on immersion in water below body temperature and by the inertial energy involved in displacing water with the chest wall during the respiratory cycle.

4.2.0 Dead Space

Almost any practical breathing device for underwater use must contain some mechanical dead space. While tolerable limits for added dead space has been defined for resting conditions such as air or oxygen breathing at sea-level pressure and at altitude, these limits are not necessarily acceptable in underwater breathing apparatus either at rest or at work. Both added external dead space and an increase in the physiological dead space tend to decrease the effective pulmonary ventilation and may readily result in values which are prohibitively low. In air, this effect may be overcome to a certain extent by increasing the tidal volume but, as briefly mentioned earlier, the inertial effects of displacing larger volumes of water, particularly at high exercise levels where the total ventilation is already appreciably increased, may be sufficiently great to make this compensatory response impractical while submerged.

4.3.0 Rapid Changes in Depth

During changes in depth, the alveolar ventilation may be effected if either ascent or descent is accomplished at a fairly high rate. On descent the gas in the respiratory spaces will be compressed and, while the respiratory movements may not vary from a normal pattern, the total amount of gas inspired will be greatly in excess of that expired and the effective ventilation for carbon dioxide elimination is thereby reduced. During ascent the process is reversed and the amount of gas exhaled is in excess of that inhaled and effective ventilation for carbon dioxide elimination is increased. If these changes in depth are extremely rapid and the respiratory movements normal, the net result in descent may approach that accomplished in breathholding; in ascent may resemble hyperventilation. If true breathholding is practiced, as in skin diving, the mass of air in the lungs remains constant, except for pulmonary exchange, and the lung volume varies inversely with depth; in this situation, effective pulmonary ventilation is essentially absent and man's performance is limited by individual tolerance to changes in lung volume and to partial pressures of oxygen and carbon dioxide in the lungs. Little study has as yet been made of the dynamics of gas exchange under any of these conditions.

4.4.0 Gas Mixtures

The effects of various gas mixtures on alveolar exchange have already been taken up in other sections of this report. These effects may be due in part to changes in the density of gases with increased pressure. In addition to the diffusion problems existing at the alveolar wall, an understanding of the flow characteristics of various gas mixtures at increased pressure in a system where the gas velocities are constantly changing is necessary for the design of adequate breathing apparatus. Information is also needed on underwater breathing patterns and instantaneous breath velocities. Since it appears from the limited amount of data available to date that individual breathing patterns exert a strong influence on the performance of CO_2 absorption canisters, these studies become increasingly important in semi-closed and closed-circuit equipment where the efficient removal of CO_2 is necessary. Again, the work in this area has thus far been limited almost entirely to an air environment at sea level or at high altitude.

4.5.0 Carbon Dioxide Removal

A considerable amount of information is available on the requirements for CO_2 absorption systems in anesthesia equipment where the relationships between canister size and breathing characteristics for resting conditions are rather well established. Design of underwater breathing equipment cannot be based upon this information because of the wider ranges for tidal volume, breath velocity, and rate of carbon dioxide production encountered in diving. The present requirements for closed-circuit fire and mine rescue equipment are such that the breathing resistance and levels of CO_2 considered permissible in this work are intolerable at the high ambient pressures encountered in diving.

While discussion of the development of specific underwater breathing equipment is outside the scope of this report, it must be emphasized that the nature of the equipment employed necessarily influences the physiological responses

to increased ambient pressure. Therefore, a sound approach to the development of such equipment cannot be made until the physical and physiological aspects of diving are more firmly established.

5.0.0 TEMPERATURE

5.1.0 Low Temperature

In addition to the great variation in surface water temperatures in different areas and seasons, a sizable differential between surface and deep-water temperature exists in many localities.

Superimposed upon the wide range of environmental temperatures are large variation in the diver's rate of metabolic activity and heat production. Since it is usually impractical for the free swimmer to perform effectively while burdened with excessive protective clothing, he is to a considerable degree limited in capacity by his environmental temperature.

5.1.1 Circulation

Most of the current studies of hypothermia, stimulated by interest in its applicability to specialized surgical procedures, are directed toward elaboration of the effects of considerably reduced body temperatures. Work in the area of prolonged exposure to low-water temperatures with moderate depression of body temperature, such as may be encountered in underwater swimming, is receiving very little attention. Not only the effects of exposure but phenomena such as the dangerous after-drop in body temperature following removal from cold water immersion require further study.

Although no method of adequately protecting the free swimmer from the loss of effectiveness during prolonged exposure to cold water is yet available, it is unlikely that this is a totally insoluble problem. Considerable progress has been made recently in the development of light exposure suits offering protection against cold air and water for individuals exposed at the surface with minimal need for mobility. Considerably more work is necessary in the more difficult development of insulating suits for the free swimmer. Furthermore, although the possibilities of the use of electricity for providing heat during submergence have not yet proved encouraging, the chemistry of certain heat producing substances and even the use of compact combustion chambers hold out considerable hope for a method of supplying external heat to the swimmer. In the diver's favor is the fact that his metabolic heat production is high while swimming vigorously; the major problem therefore becomes one of conservation rather than substitution of body heat.

5.1.2 Dietary Influences

Very little is known about dietary influences on the tolerance to cold water. Among those experienced in arctic living, there is the opinion that dietary influences are quite important in chronic situations. However, most of the evidence seems to have been obtained from exposure to dry cold and on relatively inactive individuals. This work has not been extended to the swimming man exposed to cold water.

5.1.3 The Extremities

In studies of exposure suits it has been found that one of the greatest problems of protection concerns the hands and feet. In the extremities, the relatively large surface exposed, the distance the blood must travel, and the normal vasoconstrictor response to cold, all lead to exaggerated lowering of temperature. As yet no great success has been achieved in maintaining hand and foot temperatures or manual dexterity in cold water. That this may be a fruitful area for research is suggested by the unique tolerance to cold water demonstrated by the hands of some of the Maine lobstermen.

On the basis of present knowledge any extensive physiological or pharmacological modification of human intolerance to lowering of body temperatures is not promising. Quite possibly, the principal long-range activity must be in the direction of human engineering and design of external protective mechanisms that will allow the diver to maintain a relatively constant environment inthe immediate vicinity of his skin.

5.2.0 High Temperature

Although exposure to cold in diving has received most attention, the problem of exposure to high water temperatures cannot be ignored. In the actively swimming individual the metabolic heat production is high and, if dissipation of this heat is impeded, considerable discomfort and physiologic derangement can result. Heat dissipation is considerably abetted by the high conductivity of water but if the water temperature is near or above skin temperature, this physical factor is no longer an aid to the swimmer and body temperature must rise. As in exposure to cold the end result is determined by the rate of heat loss relative to metabolic heat production.